Heavy quark production from Color Glass Condensate at RHIC

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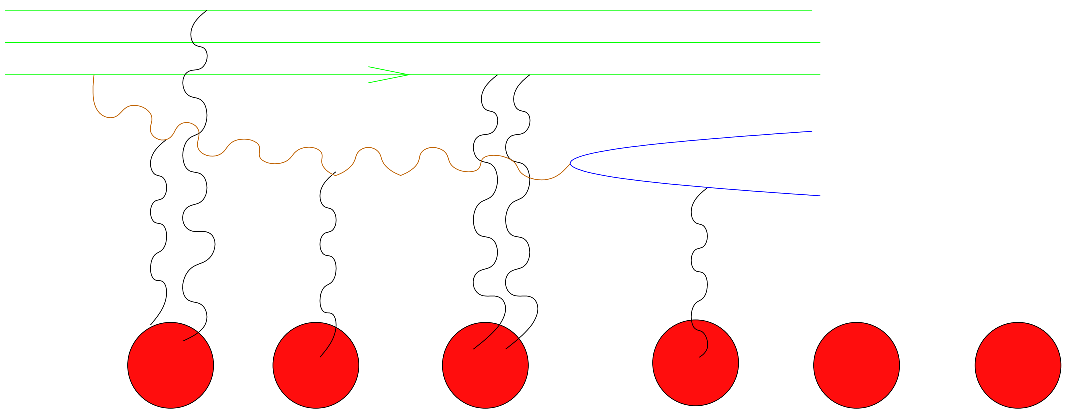
based on papers:

hep-ph/0310358 (in collaboration with D. Kharzeev)

and hep-ph/0401022

Proton (Deuteron) – Heavy Nucleus collision in the nucleus rest frame



$$\tau_{qv \to qg} = \frac{2q^+}{q_T^2}$$

where q_T is the gluon transverse momentum.

$$t_{g \to q\bar{q}} = \frac{2k^+}{k_T^2}$$

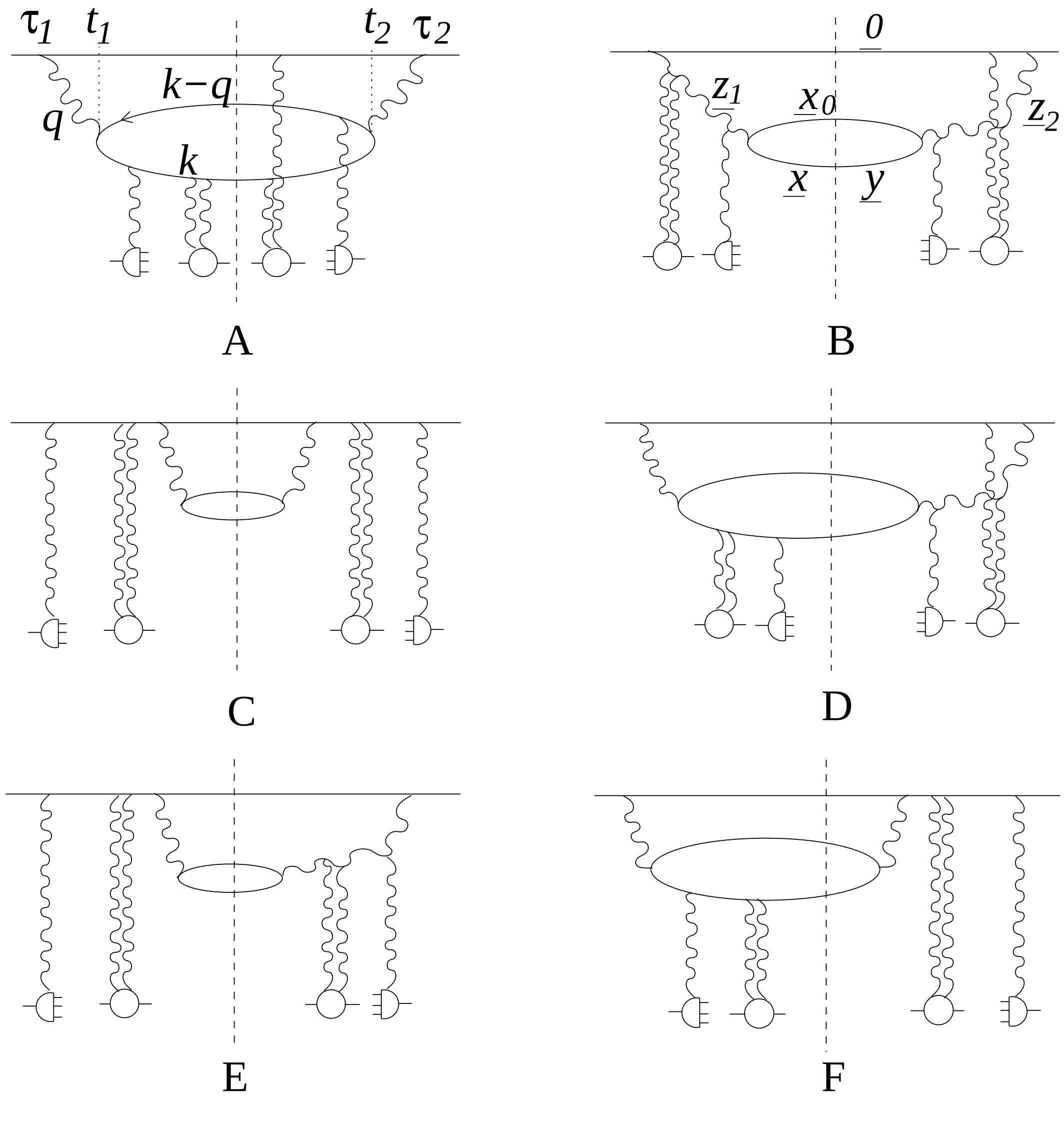
where k_T is the gluon transverse momentum.
Since $q^+ \gg k^+ \gg k_T, q_T$ we have strong ordering (Ioffe):

$$\tau_{qv \to qvg} \gg t_{g \to q\bar{q}} \gg R_A$$

Therefore, diagrams in which gluon or heavy quarks are produced in course of the rescatterings in a nucleus are suppressed by powers of energy $p^+ \sim \sqrt{s}$.

Leading order diagrams

All possible cases depending on the time of the gluon emission in the amplitude τ_1 and in the complex conjugated one τ_2, and $q\bar{q}$ pair emission in the amplitude t_1 and in the complex conjugated one t_2:



Cross section for quark production in p(d)A collisions

$$\frac{d\sigma}{d^2k\,dy} = \Phi_{qv\to qvg}(\underline{z}_1,\underline{z}_2)\otimes\Phi_{\mathrm{g}\to\mathrm{q}\bar{\mathrm{q}}}(\underline{x}-\underline{x}_0,\underline{y}-\underline{x}_0,\alpha)$$

$$\otimes\,\Xi(\underline{x},\underline{y},\underline{x}_0,\underline{z}_1,\underline{z}_2;\underline{b})\,e^{-i\underline{k}\cdot(\underline{x}-\underline{y})}$$

where Φ's are the squared light-cone wave functuions and Ξ is the Glauber-like rescattering factor. We summed up terms of the order $\alpha_s^2 A^{1/3}$ which give multiple rescatterings of a proton in a nucleus. We neglected low-x evolution terms $\alpha_s \ln(1/x)$ – OK at RHIC at $y=0$.

In the nucleus light-cone frame pA scattering can be viewed as a scattering of a proton off the $q\bar{q}$ fluctuation of a strong color field, i.e. Color Glass Condensate (McLerran & Venugopalan, Kovchegov). The chromoelectric component of that field is $E\sim\frac{Q_s^2}{g}$ where $Q_s\sim A^{1/6}\,s^{\alpha_s}$ (Gribov, Levin, Ryskin). It can produce $q\bar{q}$ pairs from vacuum if

$$gE\geq\frac{m}{\lambda}\sim m^2 \quad\Rightarrow\quad Q_s^2>m^2$$

Thus, at large s transverse structure of hadrons is of crucial importance.

k_T-factorization

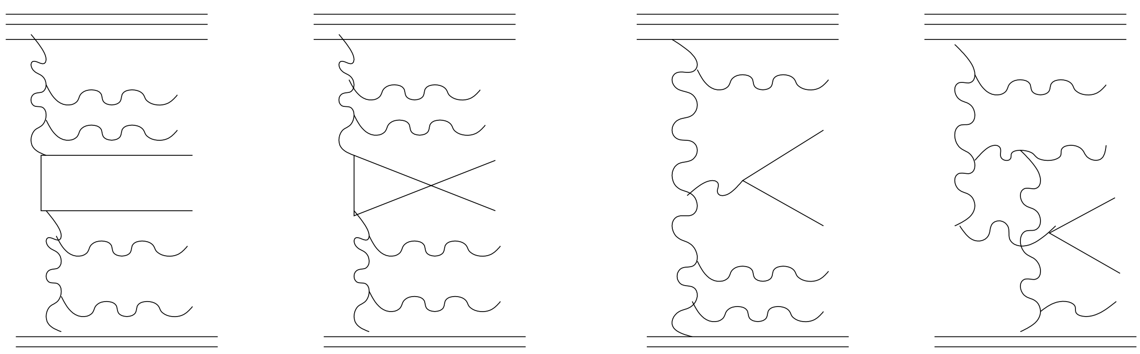
For pp scattering (at RHIC) it is possible to simplify formulas and write the k_T-factorized expression

$$\frac{d\sigma_{cc}}{d^2k_\perp\, dy_1\, dy_2} =$$

$$\int d^2 q_{\perp 1} \int d^2 q_{\perp 2}\, \phi(y_1, q_{\perp 1})\, \mathcal{A}_{gg}\, (\hat{s}, \hat{t}, \hat{u}, q_{\perp 1}^2, q_{\perp 2}^2)\, \phi(y_2, q_{\perp 2}),$$

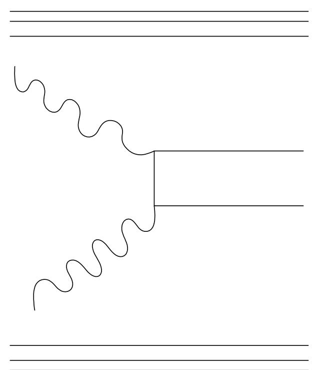
where $\phi(y, q_\perp) = \frac{dxG(y, q_\perp)}{dq_\perp^2}$ (Levin at. al. , Catani et. al. , Collins & Ellis).

These are the Feynman diagrams which contribute to $\mathcal{A}$:



It works for b-production at Fermilab! (Hägler et. al.). It is not clear if in pA case such simple formula can be written. However, we will use it for phenomenological applications to pA and AA collisions.

Collinear factorization (parton model)



Collinear factorization: the typical transverse momentum inherent to a hadron wave function is $q_T^2 \simeq Q_s^2$. If $Q_s \ll m$ it is a good *approximation* to take $q_T \to 0$ and average over its directions. Then one gets

$$\frac{d\sigma_{\rm cc}}{d^2k_\perp\, dy_1\, dy_2} = xG(y_1)\,\frac{d\hat{\sigma}_{gg}}{d\hat{t}}(\hat{s},\hat{t},\hat{u})\,xG(y_2)$$

It describes the experimental data on pp at high energies only if one introduces

1. the K factor to fix the overall normalization;
2. the intrinsic momentum $k_{\rm intr} \gg \Lambda_{\rm QCD}$ to make the calculated spectrum harder.

The k_T-factorization is free of such problems!

k_T-factorization in AA

We assume that the k_T-factorization also works for AA. In the framework of the Color Glass Condensate it is proved at the lowest order in nuclear partonic density (Gelis & Venugopalan).

Properties of the unintegrated gluon distribution of a nucleus $\phi_A(y, q_\perp)$:

1. it is black at $q_\perp \ll Q_s$, its value is known form theoretical studies of DIS (Kovchegov & Tuchin):

$$\phi_A(y, q_\perp) = \frac{4\, C_F\, S_A}{\alpha_s\, 2\, (2\pi)^2} \ln(Q_s^2/q_\perp^2)$$

2. high $q_\perp$ tail is the same as in parton model:

$$\phi_A(y, q_\perp) \sim q_\perp^{-2}$$

3. it has the geometric scaling (Golec-Biernat et. al.) built in in agreement with the nonlinear evolution equation (Balitsky, Kovchegov)

$$\phi_A(y, q_\perp) = \phi_A(q_\perp^2/Q_s^2(y))$$

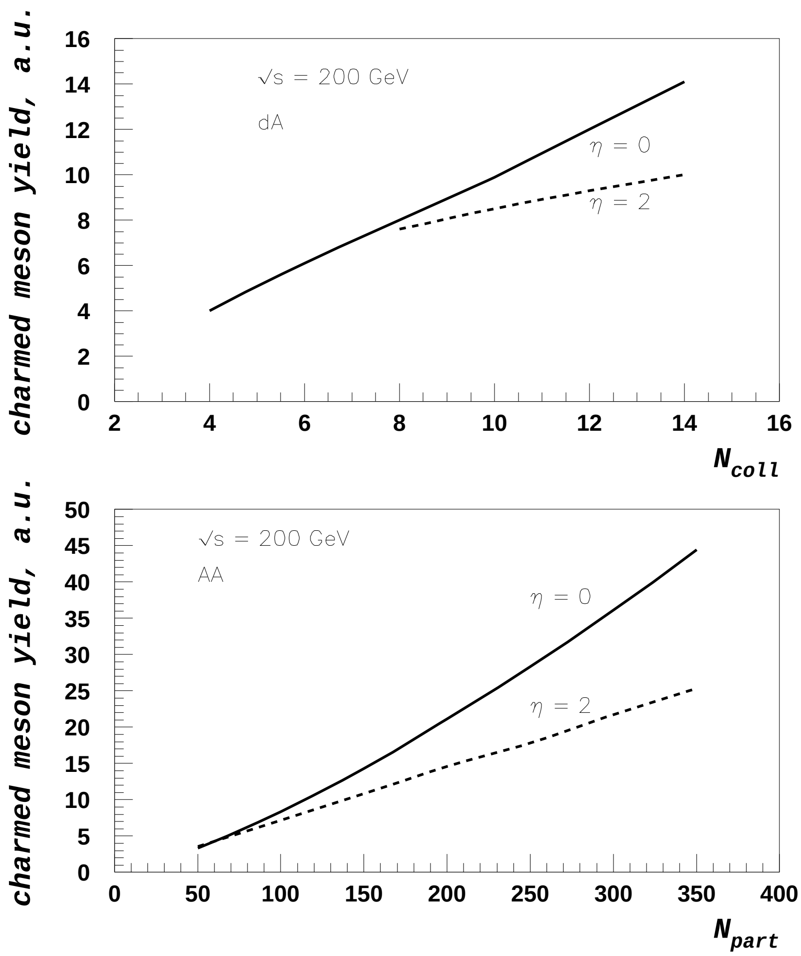
Interplay of different scales in open charm production

Mass of a charmed quark is $m \approx 1.3$ GeV. The saturation scale at RHIC is $Q_s^2 \approx 2\, e^{0.3\, y}$ GeV^2. Therefore,

- At $\eta = 0$ at RHIC $Q_s \simeq m$. The nuclear color field is not strong enough. Therefore, expect $N_{\rm coll}$ scaling
$$\frac{dN}{dy\, d^2p_\perp} \sim N_{\rm coll}$$
- At $\eta \gtrsim 2$ there are two effects
  1. Q_s becomes larger than m. The nuclear color field starts producing pairs from vacuum.
  2. Quantum corrections become large: $\alpha_s y \sim 1$. This changes the anomalous dimension of the gluon distribution function $\phi_A(y, q_T)$ at $q_\perp > Q_s$. It produces suppresion at high momenta (Kharzeev, Levin, McLerran). Therefore, expect $N_{\rm part}$ scaling
  $$\frac{dN}{dy\, d^2p_\perp} \sim N_{\rm part}$$

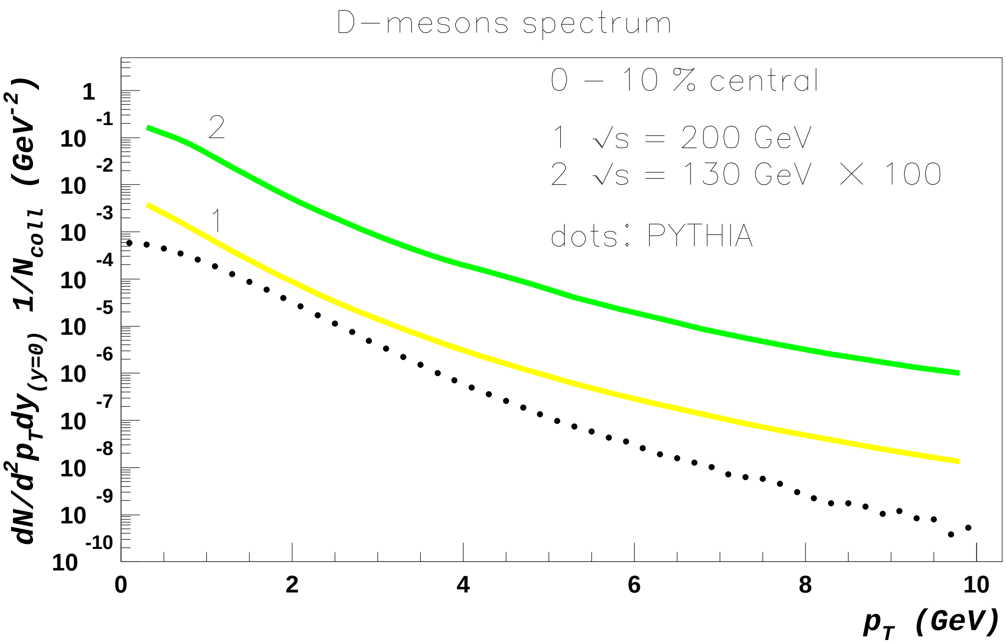
Note, that the invariant mass $\mathcal{M}$ has a large threshold $\mathcal{M}^2 \simeq 4(p_\perp^2 + m^2)$. The extended geometric scaling (Levin & Tuchin; Iancu, Itakura & McLerran) holds up to $\mathcal{M} < Q_s^2/Q_{s0}$. Therefore, the k_T-region of the extended geometric scaling for charm production is smaller than in light parton production case.

Scaling of charm spectra with atomic number A



Suppression of the charm yield is clearly seen at the forward rapidity. This is the universal feature of all semihard processes (saturation).

Open charm spectrum



Dots: results of PYTHIA model for the same parameters as used by PHENIX.

Due to $N_{\rm coll}$ scaling at $\eta = 0$ shown spectra coincide with open charm spectra in pp (at large p_T).

Final state interactions

Final state interactions produce quenching of light parton spectra (Gyulassy et. al. , Baier et. al.). The energy loss of heavy quarks is also important, however it is different in one important aspect: the angular distribution of gluon emitted in the forward direction vanishes – the dead cone effect (Dokshitzer & Kharzeev).

$$Q_H(p_\perp) \simeq$$

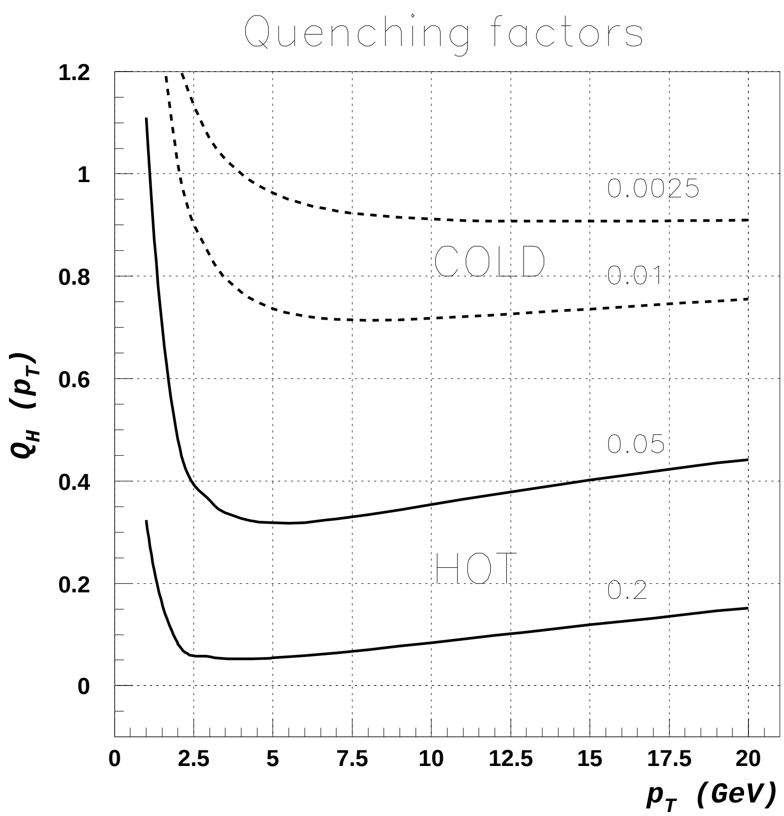
$$\exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}} L \sqrt{\hat{q}\,\frac{\mathcal{L}(p_\perp)}{p_\perp}} + \frac{16\alpha_s}{9\sqrt{3}} L \left(\frac{\hat{q}\, m^2}{m^2 + p_\perp^2}\right)^{1/3}\right],$$

where $\hat{q}$ is a transport coefficient,

$$\mathcal{L}(p_\perp) = -\frac{d}{d\ln p_\perp} \ln\left[\frac{d\sigma^{\text{vac}}}{dp_\perp}(p_\perp)\right].$$

The form of the spectrum determines $\mathcal{L}(p_\perp)$ and therefore it is essential for calculation of $Q_H(p_\perp)$.

Quenching of open charm at RHIC



$\hat{q} = 0.2,\ 0.05,\ 0.01,\ 0.0025$ GeV^3; $L = 5$ fm.

Conclusions

1. In the midrapidity $Q_s \simeq m$, and the Color Glass Condensate is represented by a quasi-classical field. Therefore open charm spectrum in AA and dA scales with number of binary collisions.

2. At forward rapidity the spectrum scales with $N_{\rm part}$. Therefore, $R_{AA}^{\rm charm}$ and $R_{dA}^{\rm charm}$ decrease with centrality at $\eta = 2$:

$$R_{\rm AA}^{\rm charm} \sim 1/A^{1/3} \sim 1/\sqrt{N_{\rm part}^{1/3}} \simeq 0.5$$

$$R_{\rm dA}^{\rm charm} \sim 1/A^{1/6} \sim 1/\sqrt{N_{\rm part}^{\rm Au}} \simeq 0.75$$

3. The open charm spectrum calculated in k_T-factorization is significantly harder than that in the parton model.

4. The quenching of the open charm spectrum is almost p_T independent at $2 < p_T < 15$ GeV due to the dead cone effect.